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Estimation of CO_2 emissions from waste incinerators: Comparison of three methods

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ABSTRACT

Climate-relevant CO_2 emissions from waste incineration were compared using three methods: making use of CO_2 concentration data, converting O_2 concentration and waste characteristic data, and using a mass balance method following Intergovernmental Panel on Climate Change (IPCC) guidelines. For the first two methods, CO_2 and O_2 concentrations were measured continuously from 24 to 86 days. The O_2 conversion method in comparison to the direct CO_2 measurement method had a 4.8% mean difference in daily CO_2 emissions for four incinerators where analyzed waste composition data were available. However, the IPCC method had a higher difference of 13% relative to the direct CO_2 measurement method. For three incinerators using designed values for waste composition, the O_2 conversion and IPCC methods in comparison to the direct CO_2 measurement method had mean differences of 7.5% and 89%, respectively. Therefore, the use of O_2 concentration data measured for monitoring air pollutant emissions is an effective method for estimating CO_2 emissions resulting from waste incineration.

1. Introduction

The United Nations framework convention on climate change (UNFCCC) was adopted in 1992 in Rio de Janeiro Brazil to cope with accelerating climate change. Based on 'The Principle of Common but Differentiated Responsibilities', all countries were motivated to reduce greenhouse gas (GHG) emissions caused by anthropogenic activities (UN, 1992). Parties under UNFCCC are required to report their greenhouse gas emissions and removals by sector as calculated according to the agreed upon methodologies. Based on the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines (GLs) for national greenhouse gas inventories (IPCC, 2006), targeted GHGs associated with waste incineration are CO_2, CH_4, and N_2O. Carbon dioxide is a major greenhouse gas which accounted for 96.5% of the gases emitted from waste incineration in Annex I countries in 2012 (UNFCCC, 2017).

There are three tier levels used to estimate CO_2 emissions from waste incineration in the 2006 IPCC GLs. The application of the higher tier levels, which use more country-specific (CS) or site specific data, is defined as a good practice (IPCC, 2006). CO_2 emissions using the Tier 1 method can be estimated using waste characteristic parameters such as waste composition, dry matter content (*DM*), carbon content (*CF*), and fossil carbon fraction (*FCF*). Tier 2 uses more CS data than Tier 1, which applies default values given in IPCC GLs. Tier 3 utilizes facility-specific data to estimate CO_2 emissions (IPCC, 2006). In recent years, the application of Tier 3, which reflects site-specific conditions and results in transparency of GHG emissions estimates, are becoming more widespread (Choi et al., 2014).

During the 2010 IPCC Expert Meeting, discussions were held on how facility-level data, including the use of gas concentration information, can be incorporated into national inventories (IPCC, 2011). Some studies suggest that facility-level data might improve national GHG inventories by using them as quality control (QC) tools, for a bottom-up approach, or for CS parameter development (Choi et al., 2017b; Hanle, 2010; IPCC, 2011, 2006; Sturgiss, 2010). Facility-level CO_2 emissions data from incineration facilities can be obtained by direct CO_2 measurements and the mass balance method according to IPCC GLs (IPCC, 2006). Another option may be the utilization of an Environmental Protection Agency (EPA) methods (40 CFR 75.13 and 60.45) that were designed to estimate

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CO_2 emissions from the combustion of fossil fuel such as coal, oil, and natural gas using O_2 concentration and fuel characteristic data.

Previous studies have reported various values for CO_2 emissions and emission factors from waste incinerators. Many of them presented *FCF* values for each composition of waste or fossil origin CO_2 fraction along with emission factors (Astup et al., 2009; Jones et al., 2014; Mohn et al., 2008, 2012; Palstra and Meijer, 2010). A study conducted by Choi et al. (2017a) estimated N_2O and CO_2 emission factors using hourly measured concentration data and compared variabilities in N_2O emission factors with CO_2 emission factors in terms of waste type, incinerator type (i.e., stoker, fluidized bed), and deNOx technology to characterize N_2O emission factors by category. Chen and Lin (2010) compared direct CO_2 measurements in flue gas with the estimated CO_2 emissions using the mass balance method following IPCC GLs and found a significant difference between the two results. However, there has been no study to explore the applicability of O_2 concentration conversion to estimate CO_2 concentration or CO_2 emissions resulting from waste incineration.

A continuous emissions monitoring system (CEMS) has been implemented to determine the compliance of industrial source air pollutant releases within many jurisdictions including in the US, Canada, Germany, UK, China, India, Japan, and South Korea (hereafter, Korea) (Guttikunda and Jawahar 2014; Jahnke, 2010; Nakamura et al., 2010; Zhang and Schreifels, 2011; Appendix A). In order to avoid dilution effects, a measurement of reference quantities of oxygen and moisture in the smokestack gas is essential in the emissions monitoring system. The reference quantities of oxygen are measured simultaneously with the concentration of pollutants in order to correct pollutant data to reference conditions for oxygen. According to '2017 White paper of Environment' published by Ministry of Environment, Korea (Appendix A), continuous air pollutant emissions monitoring has been conducted in Korea since 1998. As of 2016, seven air pollutants including dust, SO_2, NOx, NH_3, HCl, HF, and CO and O_2 at 1568 smokestacks were being measured with real-time monitoring. However, carbon dioxide has not been included in the CEMS.

In this study, we aimed to identify the applicability of continuously measured O_2 concentration data from incineration facilities of waste which is more heterogeneous than fossil fuel, to determine CO_2 emissions. Therefore, we compared the fossil CO_2 emissions (*FCO_2E*) and fossil CO_2 emission factors (*FCO_2EF*) estimated by three different methods for waste incineration facilities with and without periodic waste composition analysis. The three methods used were: making use of CO_2 concentration data, converting O_2 concentration and waste characteristic data, and using a mass balance method following the 2006 IPCC GLs.

2. Materials and methods

2.1. Waste incineration facilities and data collected

Four municipal waste incinerators (MWIs) and three industrial waste incinerators (IWIs) were selected based on the waste type (i.e., municipal waste (MSW) and industrial waste (IW), incinerator type, operation mode, and the existence of CEMS. As shown in Table 1, all seven facilities were continuously operated with stoker-type incinerators. After CO_2 analyzers were installed on the selected facilities, CO_2 and O_2 concentrations, and the flue gas flow rate were continuously measured and the parameters needed for the estimation of *FCO_2E* and *FCO_2EF* in each facility were collected or calculated (Table 1).

QA/QC (quality assurance/quality control) was conducted with CO_2 instruments (non-dispersive infrared absorption, VA-3001, Horiba; Ultramat 6, Siemens), O_2 instruments, and flue gas flow meters. O_2 instruments and flow meters on site were from various manufacturers however, they were subject to certification, regular accuracy inspection and calibration, and documentation by test standards in line with Appendix A, B, and D of EPA 40 CFR 75 (Appendix A).

Samples were collected at 30 or 60 min intervals for 24–86 days from each facility between July 2008 and September 2011 (Table 1). CO_2 and O_2 concentrations, and operating conditions (flue gas flow rate, daily waste input, furnace temperature) were compared and analyzed to screen for abnormal data. Missing or abnormally measured data were substituted for according to EPA 40 CFR Part 75. In total, a minimum of 576 and a maximum of 3744 samples were used for CO_2 emission estimation.

The daily amount of waste combusted in each facility was also obtained during the CO_2 measurement period (Table 1). Composition data associated with each measurement period for MSW were obtained from 'Annual Statistics on MWIs with energy recovery (Appendix A)' and for IW, obtained from design values (Table 2). Because proximate analysis (i.e., %moisture content, %ash content, %volatile matter content, and %fixed carbon) and elemental fraction results by each waste composition were not always available for each site, dry matter content and the mass fractions of C, H, O, N, and S by waste composition were collected from the latest and most comprehensive nationwide survey (Table 3; Appendix A). Municipal solid waste samples in the survey were stratified for rural/suburban/inner city areas, season, residential structure type (i.e., single family houses/multi-family houses/multi-story building), socio-economic class, source of waste (i.e., household/-commercial). Mass fractions of C, H, O, N, and S from ultimate analysis were based on the American Society for Testing Materials (ASTM) methods using an elemental analyzer. Waste sampling for composition analysis and proximate analysis were performed according to the 'Standard method for waste analysis (Appendix A)' that were associated with ASTM D5231 and ASTM D3173 respectively. Composition data, proximate analysis and elemental fraction results by composition are accepted for facility-level GHG management by the Korean government and also have been used in the national GHG emissions inventories submitted to UNFCCC.

2.2. CO_2 emissions estimate by direct CO_2 measurement

Total CO_2 emissions were calculated using directly measured CO_2 concentrations and associated flow rates. *FCO_2E* in a facility were calculated by multiplying the total emissions in the facility by the *FCF* value as follows:

$$FCO_2E_f(ton\ day^{-1}) = \left\{ \sum_{i=1}^{24} \frac{CO2i(\%)}{100} \times \frac{44(\mathrm{kg})}{22.4(\mathrm{m^3})} \times 10^{-3} \times Q_i(\mathrm{m^3\ h^{-1}}) \right\} \times FCF_f \quad (1)$$

where FCO_2E_f is CO_2 emissions from the fossil carbon combusted in a facility f (ton/day); CO_2 is the hourly average amount of carbon dioxide measured in the flue gas (volume%); Q is the simultaneous flow rate of the flue gas (m^3/h); FCF_f is the average weight fraction of fossil carbon in the total carbon in a facility f; and i is the measurement time.

2.3. CO_2 emissions estimate by O_2 measurement and waste characteristic data

CFR Title 40 appendix F Part 75 and Part 60 of the US *EPA* provide the procedure to determine CO_2 mass emissions from fossil fuel combustion using continuous O_2 concentration monitoring, a flow monitoring system, and fuel characteristic data. Hourly

Table 1
Characteristics of incineration facilities and parameters used in the estimation of FCO_2E (ton/day) and FCO_2EF (ton/ton) by facility.[a]

Facility[b]	Waste type[c]	Field measurement period	Number of measurement data used	Flow rate (m^3/hour)	CO_2 concentration (volume%)	O_2 concentration (volume%)	Auxiliary fuel (m^3/d)	Amount of daily waste input (ton/day)	Fossil carbon fraction	Gross calorific value (kJ/kg)
A	MSW	Feb. to May 2011 (59 days)	2832[d]	50,888	8.56	10.6	2779	176	0.40	14,690
B	MSW	Feb. to May 2011 (78 days)	3744[d]	57,250	9.75	9.00	1390	213	0.42	13,840
C	MSW	July to Aug., 2008 (24 days)	576	57,423	10.2	8.79		236	0.49	14,650
D	MSW	June to Oct., 2009 (86 days)	2064	36,120	9.72	10.0		114	0.50	13,540
E	IW	Oct. to Nov., 2010 (25 days)	600	62,371	6.95	12.7		173	0.74	32,260
F	IW	June to Sept., 2011 (61 days)	2928[d]	32,712	8.68	10.8		90	0.54	25,470
G	IW	May to Aug., 2010 (51 days)	1224	15,082	8.29	11.4		66	0.57	31,460

[a] FCO_2E_f *is* CO_2 emissions from fossil fuel originated carbon combusted in a facility f (ton/day) and FCO_2EF_f is CO_2 emission factor from fossil fuel originated carbon combusted in a facility f (ton CO_2/ton waste).
[b] Facilities A to G are continuous stoker-type incinerators.
[c] MSW: Municipal solid waste, IW: Industrial waste.
[d] 30 min interval data were used.

Table 2
Composition (weight%) of waste combusted by the incineration facilities.[a]

MWIs Waste composition	A Mean (%)	B Mean (%)	C Mean (%)	D Mean (%)	IWIs Waste composition	E Mean (%)	F Mean (%)	G Mean (%)
Paper	48.4	39.2	37.6	34.3	Paper	11.8	4	10
Textile, Leather	4.83	7.5	5.1	7.9	Textile	0.9	5	10
Plastics	20.7	18.1	27.6	27.3	Plastics	81.9	50	56
Other combustibles	0	5.6	0.0	0.0	Other combustibles	0.9	12	0
Food	9.22	10.1	21.1	15.5	Wood	0.9	4	11
Wood	7.43	7.2	4.8	7.9	Incombustible	2.7	0	0
Incombustible	9.32	12.3	3.9	7.1	Sludge	0	1	0
					Leather, rubber	0.9	14	13
					Construction and demolition	0	10	0
Sum	100	100	100	100	Sum	100	100	100

[a] Taken from 'Annual Statistics on MWIs with energy recovery (see Appendix A)'.

Table 3
Moisture content (weight%), mean elemental composition (weight%), and default percent values of FCF_j (weight%).[a]

Waste component	Moisture content (%) by proximate analysis		Ultimate analysis[b]					FCF_j (%)	
			C (%)	H (%)	O (%)	N (%)	S (%)		
	MSW	IW	MSW and IW					MSW	IW
Paper	15.9	19.4	45.1	6.37	48.2	0.23	0.04	1 (0, 5)[c]	1
Textile	14.8	1.55	55.2	6.59	35.8	2.21	0.09	20 (0, 50)[c]	16
Leather	3.3	1.6	54.6	6.28	26.6	4.07	0.34	20	17[d]
Rubber	5.8	0.2	69.5	7.37	15.6	3.73	0.91	20	17
Plastics	6.1	1.14	78.6	11.8	8.29	0.37	0.07	100 (95, 100)[c]	80
Other combustibles	44.5	3.7	51.4	6.13	38.4	3.05	0.33	100 (50, 100)[c]	3
Food	68.1	n.a	48.5	7.55	39.9	2.94	0.21	0	0
Wood	22.5	11.4	47.9	6.28	44.6	0.59	0.03	0	0

[a] FCF_j were taken from IPCC GLs (IPCC, 2006); Moisture content by proximate analysis and elemental fraction by ultimate analysis from nationwide survey results, 'The 4th survey on national waste (2011–2012)' (see Appendix A).
[b] Elemental fraction of C, H, O, N, S are for combustible material among moisture, combustible material, and ash.
[c] Upper and lower limits for FCF_j value were given only for four MSW components in 2006 IPCC GLs.
[d] Assumed same as FCF_j value for rubber because not provided in 2006 IPCC GLs.

average CO_2 concentration can be calculated from the measured hourly average O_2 concentration using the following equation.

$$CO_2(\%) = 100\frac{F_c(m^3\,J^{-1})}{F(m^3\,J^{-1})}\frac{20.9(\%) - O_2(\%)}{20.9(\%)} \quad (2)$$

where CO_2 is the calculated hourly average concentration of carbon dioxide (volume%); F_c is the ratio of the volume of CO_2 generated to the calorific value of the fuel combusted (m^3/J); F is the ratio of the volume of dry flue gases generated to the caloric value of the fuel combusted (m^3/J); *20.9* is the concentration of oxygen in the atmosphere (volume%); and O_2 is the hourly average content of oxygen measured in the flue gas (volume%). FCO_2E_f (ton/day) can be calculated by applying the CO_2 from Eq. (2) in Eq. (1).

The F and F_c values of coal, petroleum coke, tire derived fuel, oil, gas, and wood are provided in CFR Title 40 appendix F Part 75 however, no values are offered for wastes so Eqs. (3) and (4) according to CFR Title 40 Part 60 were used to generate appropriate F and F_c factors for waste combusted as follows:

$$F(\mathrm{m^3\ J^{-1}}) = \frac{227.2 \times \mathrm{H}(\%) + 95.5 \times \mathrm{C}(\%) + 35.6 \times \mathrm{S}(\%) + 8.7 \times \mathrm{N}(\%) - 28.7 \times \mathrm{O}(\%)}{GCV(\mathrm{kJ\ kg^{-1}})} \times 10^{-6} \quad (3)$$

$$F_c(\mathrm{m^3\ J^{-1}}) = \frac{2.0 \times \mathrm{C}(\%)}{GCV(\mathrm{kJ\ kg^{-1}})} \times 10^{-5} \quad (4)$$

where *H, C, S, N, O* are content of hydrogen, carbon, sulfur, nitrogen, and oxygen (weight%), respectively and GCV is gross calorific value of waste (kJ/kg).

The results from the ultimate analysis for waste composition were used to obtain the percentage of *H, C, S, N,* and *O* (Table 3). *GCVs* of waste combusted in each MWI were collected from monthly analyzed results based on ASTM using a bomb calorimeter (Table 1; Appendix A). For IWs which did not have available *GCVs*, *GCVs* were calculated using the Dulong's formula with the designed values for waste composition in each facility (Tables 1 and 2) and nationwide survey results of moisture content and elemental fraction (Table 3).

2.4. CO_2 emissions estimate by the IPCC GLs mass balance method

Using the IPCC GL model, FCO_2E (ton/day) was calculated from solid waste incineration based on the amount of waste incinerated, compositional fraction, *DM* in the waste, *CF*, *FCF*, and *OF* (oxidation factor) as follows (IPCC, 2006):

$$FCO_2E_f(ton\ day^{-1}) = SW_f(ton\ day^{-1}) \times \sum_j (WF_{jf} \times DM_j \times CF_j \times FCF_j \times OF) \times \frac{44}{12} \quad (5)$$

where SW_f is the total amount of solid waste as wet weight incinerated in a facility *f* (ton/day); WF_{jf} is the weight fraction of waste type/material of component *j* in the *SW* in a facility *f*; DM_j is the dry matter content by weight in component *j* of the *SW* incinerated; CF_j is the weight fraction of carbon in the dry matter of component *j*; FCF_j is the weight fraction of fossil carbon in the total carbon of component *j*; *OF* is the oxidation factor; 44/12 is the conversion factor from C to CO_2; and *j* is the component of the *SW* incinerated such as paper or cardboard, textiles, leather, rubber, plastics, food waste, wood waste, and other combustible wastes.

Tables 2 and 3 present the values of the input parameters (i.e., WF_j, CF_j, FCF_j, and moisture content for DM_j) used. As for *OF*, a default value of '1' provided in the 2006 IPCC GLs for all waste compositions was used.

2.5. Fossil carbon fraction and fossil carbon dioxide emission factor in a facility calculation method

Although CO_2 emissions from waste incineration is directly released into the atmosphere and provide a real contribution to the greenhouse effect, CO_2 emissions from the combustion of material of biogenic origin in waste is considered to be climate-neutral. Thus, only the climate-relevant CO_2 emissions from fossil fuel origin are considered for GHG reduction (Johnke, 2002). Since waste is a mixed fuel of fossil and biogenic origin, CO_2 emissions from fossil fuel originated waste should be quantified and reported separately (IPCC, 2006; Jones et al., 2014; Mohn et al., 2012; Palstra and Meijer, 2010; Staber et al., 2008).

The IPCC GL method estimates FCO_2E using the *FCF* value for each waste composition as described in Eq. (5) (Table 3). However, the other two methods estimate total CO_2 emissions by multiplying flow rate with CO_2 (%). Thus, the FCF_f should estimate FCO_2E_f from total CO_2 emissions (Eq. (1)). The FCF_f used in Eq. (1) can be estimated using the following equation (Choi et al., 2017a):

$$FCF_f = \frac{\sum_j (WF_{jf} \times DM_j \times CF_j \times FCF_j)}{\sum_j (WF_{jf} \times DM_j \times CF_j)} \quad (6)$$

where FCF_f is the average fossil carbon fraction in facility *f*. The other parameters are explained in Eq. (5).

Tables 2 and 3 show the waste compositional fraction for WF_{jf}, moisture content for DM_j, and the total carbon content for CF_j required in Eq. (6), respectively. Default *FCF* values were applied (Table 3) for the composition of MSW and IW as provided in the 2006 IPCC GLs for FCF_j in Eq. (6).

Fossil fuel originated CO_2 emission factors can be obtained by dividing FCO_2E_f (ton/day) by SW_f (ton/day).

$$FCO_2EF_f(ton\ ton^{-1}) = \frac{FCO_2E_f(ton\ CO_2\ day^{-1})}{SW_f(ton\ waste\ day^{-1})} \quad (7)$$

where FCO_2EF_f is CO_2 emission factor from fossil fuel origin carbon combusted in a facility *f* (ton CO_2/ton waste).

2.6. Comparison of fossil originated CO_2 emissions estimates

The Kolmogorov-Smirnov normal distribution and Spearman rank correlation coefficient tests were used to assess the relationship between CO_2 and O_2 concentrations and the relationship of the calculated FCO_2E_f using the three methods. SPSS (v.21.0.0.2, IBM SPSS Statistics) was used for the statistical tests.

3. Results and discussion

3.1. Fossil carbon fraction

Given that there are few studies on the FCF_j from waste incineration in Korea, the IPCC default FCF_j (Table 3) was used to derive a waste composition-weighted FCF_f value for each facility according to Eq. (6). The FCF_f values were 0.40, 0.42, 0.49, and 0.50 for the MWIs (Choi et al., 2017a) and 0.74, 0.54, 0.57 for the IWIs (Table 1). This increase for IWIs reflects a higher proportion of waste that originated from fossil fuels such as petroleum products or plastics (Table 2).

For comparison the mean FCF_f published in the background paper IPCC Good Practice Guidance (2002) ranged from 33 to 50% (Johnke, 2002). These values are in line with more recent published data. For example using ^{14}C-analysis for seven waste incineration facilities in Sweden, values of 0.36 and 0.38 were measured for solid and gaseous samples, respectively (Jones et al., 2014). Astrup et al. (2009) presented FCF_f of 0.33 for a European MSW (Astrup et al., 2009). The FCF_f emitted from a waste incinerator in Switzerland were 0.47 and 0.48 when determined by $^{14}CO_2$ and mass balance (Mohn et al., 2008), respectively in accordance to results of a long-term study for the same incinerator (Mohn et al., 2012). In the Netherlands, a similar share of FCF_f was determined for a waste incineration facility (average value of 0.51 based on ^{14}C analysis of flue gas CO_2 from 13 samples) (Palstra and Meijer, 2010).

3.2. Using the CO_2 measurement method

Estimation of FCO_2E_f (ton/day) resulting from waste incineration requires distinctions between the waste and auxiliary fuel car-

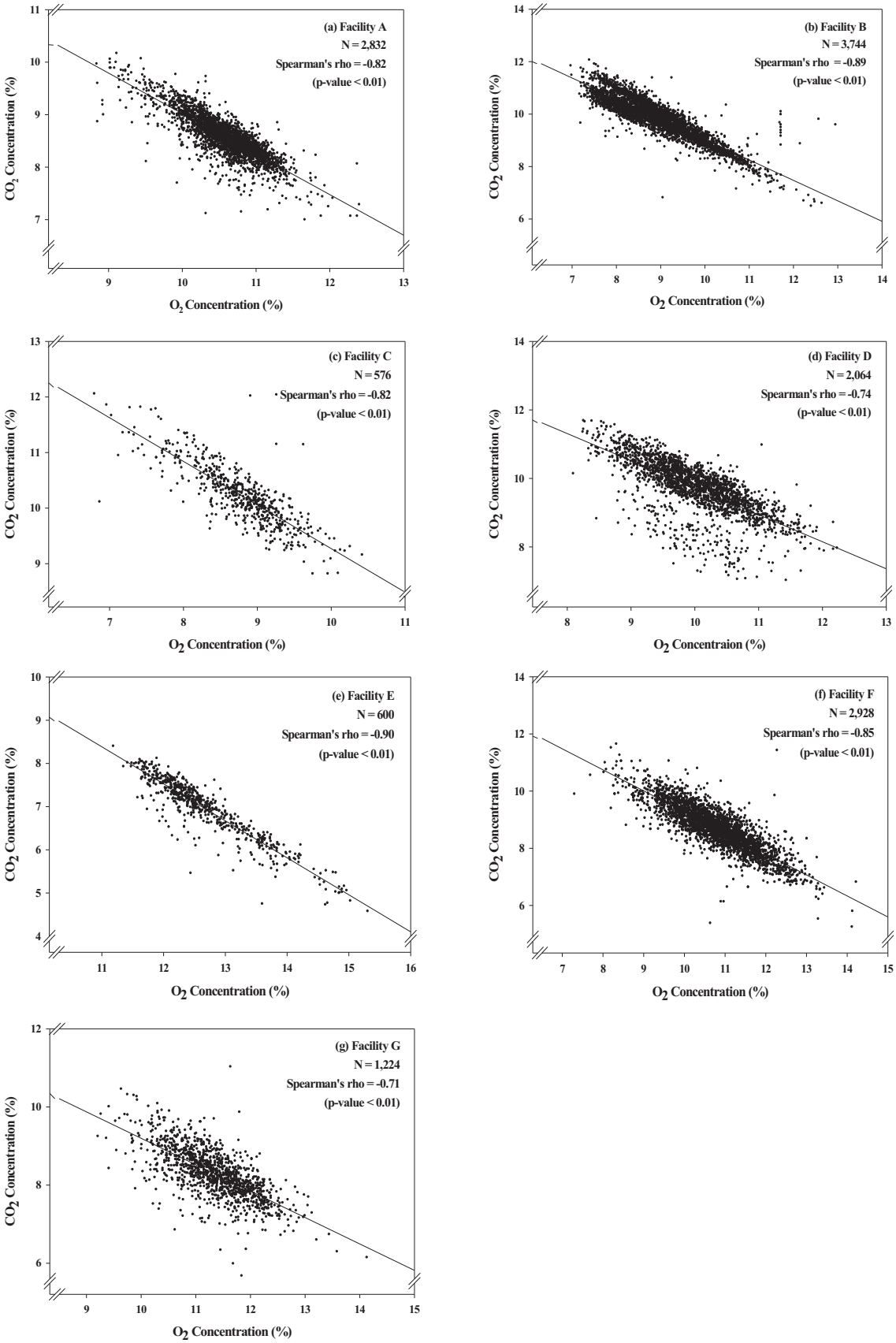

Fig. 1. Relationship between CO_2 and O_2 concentration (volume%).

bon as well as between fossil and biogenic carbon in the waste. A previous study showed that carbon contained in waste and fuel oil accounted for 99.9% of the total C input in a waste incineration facility which suggests that the measured CO_2 concentration in flue gas was largely due to the combustion of carbon in waste and auxiliary fuel (Reinhardt et al., 2008).

Because liquefied natural gas (LNG) was used as an auxiliary fuel in Facilities A and B, CO_2 emissions due to the auxiliary fuel were calculated and subtracted from the total CO_2 emissions in the flue gas. A CO_2 emission factor (56,100 CO_2 kg/TJ) for LNG from the 2006 IPCC GLs and a CS lower heating value of LNG (40 MJ/Nm^3) from enforcement rule of the Energy Act, Korea (Appendix A) were used to estimate CO_2 emissions due to LNG combustion. Estimated FCF_f was used to derive FCO_2E_f as described in Eq. (1).

3.3. Using the O_2 conversion method

Concentrations of O_2 and CO_2 in flue gas vary depending on the types of fuels (i.e., waste) and portion of excess air (Buekens, 2013; North American Combustion Handbook, 1978). CO_2 generation is proportional to the amount of carbon burned (North American Combustion Handbook, 1978). When perfect combustion occurs, the flue gas will have zero% O_2 and maximum% CO_2 (North American Combustion Handbook, 1978). However, excess air is always supplied to ensure complete combustion of fuel resulting in an increase of oxygen content and a decrease of CO_2 content in the flue gas (North American Combustion Handbook, 1978). Fig. 1 described this negative relationship between flue gas CO_2 and O_2 concentrations. Because CO_2 and O_2 concentrations in most facilities showed non-normal distributions as measured by the Kolmogorov-Smirnov tests, a Spearman's rank correlation coefficient was used to analyze the relationship between CO_2 and O_2 concentrations. Spearman's rank correlation coefficients ranged from −0.71 to −0.90 with p-values below 0.01 for all incineration facilities, which verify strong negative correlations between CO_2 and O_2 concentrations (Fig. 1). Similarly, Spearman's rank correlation coefficients for daily FCO_2E_f estimated using CO_2 and O_2 measurements at seven study sites ranged from 0.71 to 0.93 with p-values below 0.01.

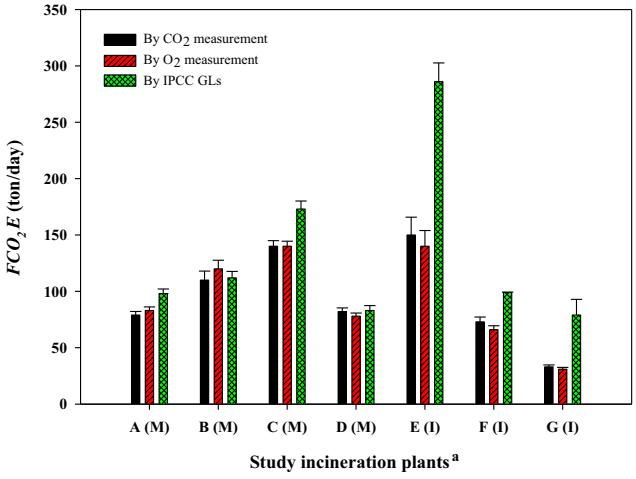

Fig. 2. Comparisons of FCO_2E_f (ton/day) estimated by three different methods. [a]M and I in round bracket stand for MWI and IWI respectively.

3.4. Using the mass balance method of the IPCC GLs

As mentioned above, FCO_2E_f estimated using the IPCC GL method is determined by the quantity of daily waste input, WF_{jf}, DM_j in the waste, CF_j, FCF_j, and OF (Eq. (5)). Therefore, the accuracy and precision of FCO_2E_f estimated by the IPCC GL method depends mainly on the information on the combusted waste.

3.5. Fossil CO_2 emissions estimated for MWIs using analyzed values of waste composition

Fossil originated CO_2 emissions (ton/day) calculated using the CO_2 measurement method were compared with those using the other two methods (Fig. 2; Table 4). The estimated FCO_2E using this method is not 'true fossil originated CO_2 emissions', but are considered closer to the 'true value' than using the other two methods.

In comparison to the direct CO_2 measurements, the absolute differences in FCO_2E_f (ton/day) estimated by using the O_2 conversion method was smaller than using the IPCC GLs. The differences in FCO_2E_f between the O_2 conversion method and the direct CO_2 measurement ranged from 0 to 9.1% for the four MWIs. The differences in FCO_2E_f (ton/day) calculated using the IPCC method and the direct CO_2 measurement were between 1.2 and 24%. The mean absolute differences in FCO_2E_f (ton/day) estimated by using the O_2 conversion method and the IPCC method were 4.8 and 13% respectively.

3.6. Fossil CO_2 emissions estimated for IWIs using designed values of waste composition

The daily mean FCO_2E_f (ton/day) difference between the IPCC GL and direct CO_2 measurement was the highest (140%) for IWI Facility G, followed by IWI Facilities E (91%) and F (36%) (Fig. 2; Table 4). However, the absolute differences in FCO_2E_f (ton/day) between the O_2 conversion and direct CO_2 measurement were much smaller and similar at 6.7%, 9.6%, and 6.1% at IWI Facilities E, F, and G, respectively (Fig. 2; Table 4). The differences in FCO_2E (ton/day) between the direct CO_2 measurement and IPCC GL methods were 89% on average for the IWIs.

The larger mean difference for the IWIs (89%) than for MWIs (13%) between the IPCC GL and direct CO_2 measurement methods

Table 4
FCO_2E (ton/day) and FCO_2EF (ton/ton) estimated by the three methods.

MWIs	A			B			C			D			Average	
Method	CO_2	O_2	IPCC	CO_2	O_2	IPCC	CO_2	O_2	IPCC	CO_2	O_2	IPCC	O_2	IPCC
FCO_2E (ton/day)	79	83	98	110	120	112	140	140	173	82	78	83		
FCO_2EF (ton/ton)	0.45	0.47	0.56	0.52	0.56	0.53	0.59	0.59	0.73	0.72	0.68	0.73		
Mean difference compared to by CO_2 measurement (%)		5.1	24		9.1	1.8		0.0	24		−4.9	1.2	4.8	13
IWIs	E			F			G						Average	
Method	CO_2	O_2	IPCC	CO_2	O_2	IPCC	CO_2	O_2	IPCC				O_2	IPCC
FCO_2E (ton/day)	150	140	286	73	66	99	33	31	79					
FCO_2EF (ton/ton)	0.87	0.81	1.7	0.81	0.73	1.1	0.50	0.47	1.2					
Mean difference compared to by CO_2 measurement (%)		−6.7	91		−9.6	36		−6.1	140				7.5	89

was probably due to the inaccurate waste information that used design values for waste composition (Tables 2 and 4). 'Plastics' was the most plentiful component, occupying 81.9, 50, and 56% at IWI Facilities E, F, and G, respectively. At the four MWI facilities, 'plastics' accounted for the second largest portion, ranging from 18.1 to 27.6% (Table 2). To determine the contribution by waste

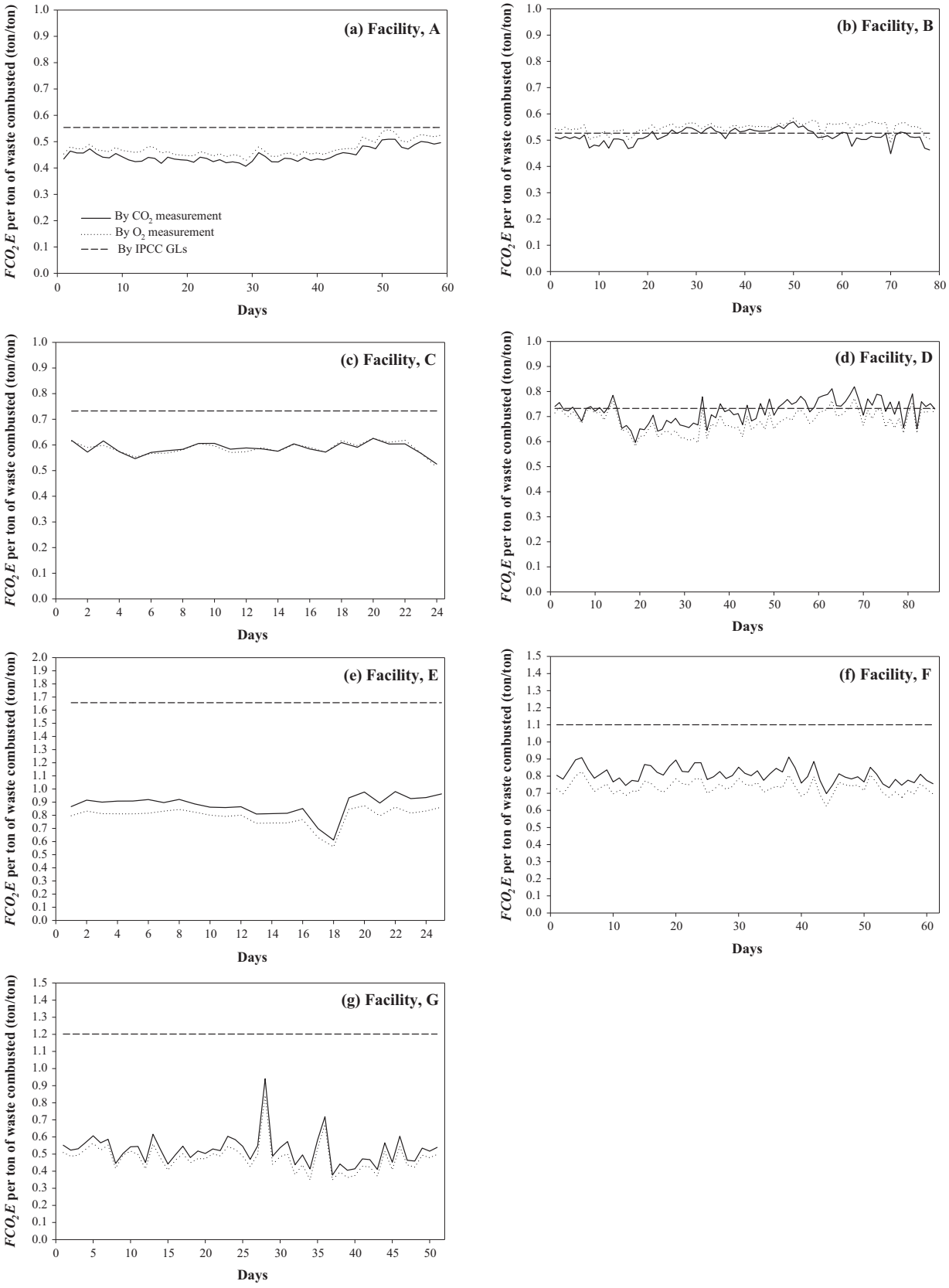

Fig. 3. Comparisons of FCO_2EF (ton/ton) trend estimated by three different methods.

composition to the differences in FCO_2E (ton/day) between IPCC GL and direct CO_2 measurement methods, correlations between weight fraction by waste composition and the difference in each facility were analyzed for the seven incineration facilities. The difference in FCO_2E (ton/day) estimated by the two methods were negatively correlated with both 'food' and 'incombustible' at -0.80 of spearman's rho ($p < .05$). The weight fraction of 'plastics' showed a positive correlation at 0.83 of spearman's rho ($p < .05$).

As mentioned above, 'plastics' accounted for the largest portion in the three IWIs where waste composition data were not available. As shown in Table 2, 'food' was not included in any IWI Facility and 'incombustible' was included in only one IWI Facility E. Thus it is inferred that the larger mean difference in FCO_2E (ton/day) between the IPCC GL and direct CO_2 measurement methods for the three IWIs were related with the inaccurate waste information particularly a much larger portion of 'plastics' and smaller portion of 'food' and 'incombustible' in the waste.

The significance of the 'plastics' portion in estimating FCO_2E from waste incineration can be explained by higher *DM* (93.9%), the highest *CF* (78.6%) and *FCF* (100%) values for 'plastics' among various components of waste (Table 3). These high values of *DM, CF, and FCF* were in agreement with default values found in IPCC GLs of 100, 75, and 100% respectively. A previous study (Johnke, 2002) indicated that the lack of representative waste samples could cause large CO_2 emissions estimation errors using the IPCC GL method. Thus, the accuracy in FCO_2E estimated by IPCC GL method may be improved by conducting an analysis on waste composition and refining the technique for representative sampling of the waste so its content can be better defined.

3.7. Comparison of fossil CO_2 emission factor time series

Fig. 3 shows the trend in FCO_2EF (ton/ton) during the CO_2 measurement periods for each facility. The time series of FCO_2EF_f estimated by the O_2 conversion were in good agreement with those estimated using the direct CO_2 measurements. However, FCO_2EF_f calculated using the mass balance method of the IPCC GLs show very different trends with no change over time. O_2 and CO_2 concentrations are simultaneously influenced by the conditions in the combustion chamber and the operating status, which include shutdown, start-up, malfunction, and the change in fuel characteristics. The FCO_2EF_f for the MWIs estimated by the direct CO_2 measurement, O_2 conversion, and IPCC GL methods ranged from 0.45 to 0.72 (Choi et al., 2017a), 0.47 to 0.68, and 0.53 to 0.73, respectively (Table 4). These results are comparable to previous studies (Chen and Lin, 2010; Johnke, 2002). For example in a study on MSW incineration in Germany, FCO_2EF were 0.415 ton of CO_2 per ton of MSW (Johnke, 2002). Chen and Lin (2010) estimated 0.567 ton of CO_2 per ton of MSW combusted.

The differences in FCO_2EF_f estimated by the IPCC GL method and the other two methods for IWIs using designed values for waste composition were much larger than those for MWIs (Table 4; Fig. 3).

4. Conclusions

The IPCC GLs recommend applying higher tier methods that reflect site-specific conditions to improve GHG emissions inventories and reduce on-site GHG emissions. GHG emissions from waste incineration facilities are regulated, or under an emission trading system, in many countries. The CO_2 emissions estimate method used can be selected depending on the required accuracy and available resources. The IPCC GL method is a quick and convenient method but largely depends on waste information. Continuous CO_2 emissions monitoring is considered more accurate but can be expensive due to the CO_2 analyzer cost. The use of O_2 concentration data measured for monitoring air pollutant emissions might be an effective alternative method for estimating CO_2 emissions resulting from waste incineration.

This study showed that real time O_2 concentrations could be used to address the differences between FCO_2E_f calculated using direct CO_2 measurements and FCO_2E_f estimated using only waste characteristic data. The O_2 conversion method in comparison to the direct CO_2 measurement method had a 4.8% mean difference in daily CO_2 emissions for four incinerators where analyzed waste composition data were available. For the three IWIs where analyzed waste composition data were not available, the differences in calculated daily mean FCO_2E_f between the CO_2 measurement and the O_2 conversion methods were estimated at a minimum of 6.1% and a maximum of 9.6%. These results were in contrast to the difference between the CO_2 measurement and the IPCC methods, which showed a much larger variation from 36% to 140%.

Notes

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Appendix A

Waste type, incinerator type, capacity, and operation mode by incineration facility were obtained from "The status of generation and treatment of national waste, 2009. ENVICO-RF-2009-23-45 (in Korean)".

This was accessed at http://library.me.go.kr/viewer/MediaViewer.ax?cid = 1,99,849&rid = 32&moi = 3,04,544 (October 7, 2017).

GCVs and composition data for each municipal waste incinerator (MWI) were obtained from "Annual Statistics on MWIs with energy recovery, from 2008 to 2013, Management Council of nationwide MWIs with energy recovery (in Korean)"

This was accessed at

http://www.me.go.kr/home/web/policy_data/read.do?pagerOffset = 50&maxPageItems = 10&maxIndexPages = 10&searchKey=&searchValue=&menuId = 10,265&orgCd=&condition.code = A6&condition.deleteYn = N&seq = 5117 (October 7, 2017).

Nationwide survey results of moisture content and elemental fraction of waste were obtained from "The 4th survey on national waste (2011 ~ 2012), 2013, Ministry of Environment, Korea (in Korean)"

This was accessed at

http://webbook.me.go.kr/DLi-File/091/018/005/55,52,489.pdf (October 7, 2017).

Composition analysis and proximate analysis were performed according to 'Standard method for waste analysis, 2016 (Ministry of Environment, Korea)' under the Environmental Testing and Inspection Act of Korea (in Korean).

This was accessed at http://www.me.go.kr/gg/web/board/read.do?menuId = 2246&boardId = 7,88,150&boardMasterId = 228&condition.hideCate = 1 (October 16, 2017).

Country specific lower heating value of LNG were obtained from "An Attached Table of Enforcement Rule of the Energy Act, Korea (in Korean)".

This was accessed at www.law.go.kr (October 7, 2017).

Operating status on CEMS in Korea were obtained from "2017 White paper of Environment, Ministry of Environment, Korea (in Korean)"

This was accessed at http://webbook.me.go.kr/DLi-File/091/025/006/56,36,222.pdf (October 7, 2017).

The procedure to determine CO_2 concentration or CO_2 emissions using an O_2 monitor were in accordance with "Specific provisions for monitoring CO_2 emissions 40 CFR, part 75.13" and "Appendix F to Part 75", and "Emissions and fuel monitoring 40 CFR, part 60.45".

These were accessed at https://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr75_main_02.tpl (October 25, 2017).

https://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr60_main_02.tpl (October 25, 2017).

CO_2 and O_2 concentrations, and the flue gas flow rate were measured in accordance with the "Test standards of air pollution" under the Environmental Testing and Inspection Act of Korea (in Korean)".

The test standards were accessed at http://www.law.go.kr/%ED%96%89%EC%A0%95%EA%B7%9C%EC%B9%99/%EB%8C%80%EA%B8%B0%EC%98%A4%EC%97%BC%EA%B3%B5%EC%A0%95%EC%8B%9C%ED%97%98%EA%B8%B0%EC%A4%80 (October 16, 2017).

Certification and QA/QC of CO_2 and O_2 instruments and flue gas flow meters were subject to "Notification on the approval and accuracy inspection of environment measuring instrument (National Institute of Environmental Research, 2013)" under the Environmental Testing and Inspection Act of Korea (in Korean) and were in line with Appendix A, B, and D of US EPA 40 CFR 75.

These were accessed at http://www.lawnb.com/data/Focuslawdata/lawnbfocusB0004581320.pdf (October 16, 2017).

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